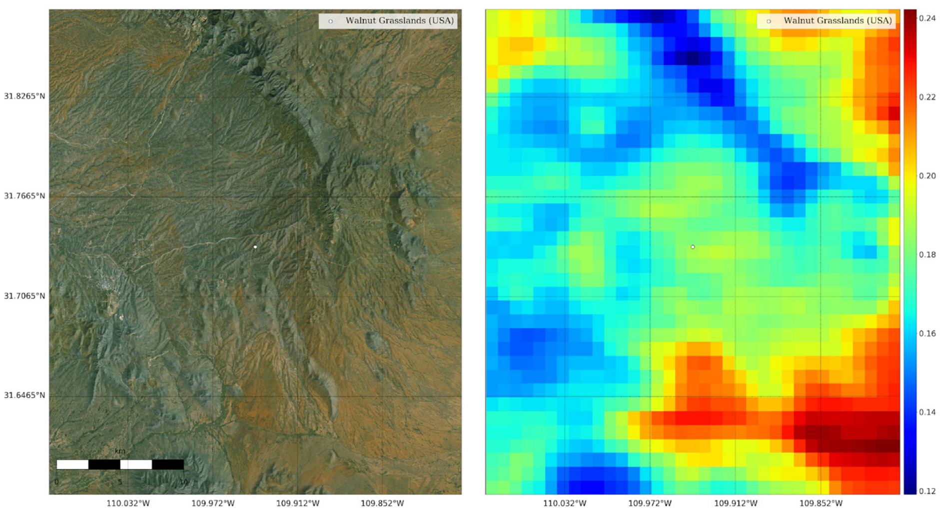
Albedo for bifacial PV projects — Part II

How to extract valuable data from albedo measurements



Whitepaper

Solargis research 2021

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Overview

Reducing uncertainty of albedo estimates using albedometers

The emergence of bifacial photovoltaic (PV) module technology has led to the need for reliable ground albedo data. In these regards, a combination of ground measurement campaigns based on high-quality albedometers and global data albedo sources based on satellite observations provide the best possible results.

Ground observations are considered as a reference for a specific location, provided the high-quality instruments are used, correctly installed (location, mounting), with rigorous O&M following recommendations of the sensor manufacturers and best practices.

Ground observations are considered the reference for a specific location, provided the high-quality instruments are used, and proper installation and O&M

The objective of this white paper is to provide recommendations on how to measure onsite albedo for PV applications and how to extract the best value from the data. We discuss best practices for measuring albedo at areas eligible for hosting a bifacial PV project and methods for reducing the bias of global albedo data sources.

How does an albedometer work?

Surface albedo can be measured by means of an instrument called albedometer. It consists of two pyranometers arranged in opposite directions parallel to the horizontal surface, and measuring synchronously global horizontal irradiance (GHI) and reflected horizontal irradiance (RHI), respectively.

One of the pyranometers measures GHI and the other RHI. So albedo is directly obtained using the equation:

$$\rho = \frac{RHI}{GHI} \quad \text{where,}$$

RHI is the total reflected irradiance scattered back by the ground surface reaching the horizontal surface.

GHI is the global (or total) solar irradiance reaching the horizontal surface.

Fig. 1: Hukseflux SRA11 albedometer.

Obtaining representative values for a PV project

As discussed in ‘Albedo for bifacial PV projects — Part I’ white paper, albedo has high spatial and temporal variability.

> The spatial variability of albedo within the same area highlights the importance of combining ground measured with satellite-based values

On one hand, understanding the variability of albedo throughout the power plant lifetime is crucial for energy yield assessments. On the other hand, one should look at the data representativeness and check how albedo changes across the project area. The spatial variability of albedo within the same area highlights the importance of combining ground measured albedo with satellite-based values, to cover the entire project area.

Variability of albedo within the project area

Desert regions, such as Atacama, Chile, where geographical conditions provide relatively high bifacial gains, show a wide variety of ground albedo values. For yield assessment studies for bifacial PV projects one should conduct a preliminary study on the ground surface homogeneity.

Fig. 2: Surface around the PV power plant area Cerro Dominador in Chile. Source: Google Maps.

Key considerations for albedometer installations

Installation height

The height of the instrument is directly related to the area covered by the field of view (FOV) of the downward-facing pyranometer, and therefore it determines the area which the measured albedo values represent.

The area covered by the field of view (FOV) of the downward-facing pyranometer is theoretically unlimited, i.e. it covers the entire surface up to the horizon (180°). In practice, however, the majority of the energy captured by the downward-facing instrument measuring RHI comes from a limited circle-shaped area sustained by the conical FOV and centered around the instrument position.

> In practice, the majority of the energy captured by the downward-facing instrument comes from a limited circle-shaped area

It is important to note the large differences between the sizes of the areas covered by the albedo data. For the sake of comparison with the albedometer FOV area, we calculate an area of the highest nominal resolution of the regular pixel of MODIS (in geographical coordinates projection) in the example below.

For instance, the total reflected energy, RHI, measured by an instrument installed at a height of 2 meters comes from a circle-shaped area of 616 m2. On the other hand, the satellite pixel with 500 m resolution covers a square-shaped area of 250,000 m2. This reinforces the recommendation to carefully consider the representativeness of both the albedo measured by the instrument and the albedo estimated by the satellite.

Bifacial gains for different PV configurations

Although a wide range of albedo values is shown for completeness, the vast majority of cases on land are actually constrained to the albedo value range between 0.1 and 0.3.

Albedometer					**Satellite (MODIS)**	
Inst. heigh [m]	1.5	2	10	30		
FOV radius [m]	10.5	14.0	70.2	210.5	**Pixel size [m]**	500
FOV area [m²]	346	616	15,482	139,205	**Pixel area [m²]**	250,000

Tab. 1. Examples of surface areas covered by the instrument FOV for different installation heights.

The selection of the installation height involves the proper pondering of the area covered by the instrument's FOV with respect to the total area of interest (e.g. the surface covered by the solar field of a PV power plant).

In some cases, it may be necessary to install several instruments over the site to cover the different surface properties inside the solar field to obtain the average (representative) value, while for the satellite data one single dataset may be sufficient.

There are other factors to consider related to the height, such as the instrument's accessibility for the O&M works (cleaning, leveling and maintenance). It is also important to consider errors due to self-shading, which is most relevant at lower installation heights.

Instrument FOV (Field of View)

The radius of the covered area directly depends on the installation height (h).

Thus, for example, for an installation height of 1.5 meters above the ground, 99% of the reflected energy measured by the downward-facing instrument comes from a circle-shaped area with a radius (r) of 10.5 m (i.e. an area of 346 m²).

If the downward-facing pyranometer is equipped with a glare-screen to prevent direct sun illumination at sunrise and sunset the radius of the subtended area varies according to the equation:

$$r = h \cdot \tan(90 - \gamma),$$

where γ is the shield angle (in degrees, typically around 10°)

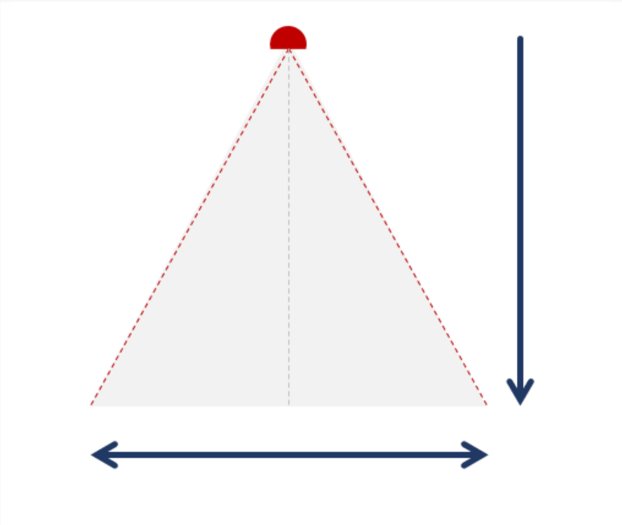

Fig. 3: Representation of instrument's FOV.

Nearby obstacles

In case of reflected horizontal irradiance (RHI), as with other radiometric instruments, it is desirable that there are no obstacles and/or sources of external light emission, such as high reflective objects, that could artificially influence the measurements.

The closer the objects are to the albedometer, the more they will affect the measurements. The measurements affected by nearby objects will not only misrepresent the characteristics of the surface but will also suffer from specular reflections.

Works on the ground

Albedo may be affected by changes in terrain surface due to the installation of equipment at the meteorological site. This may change the ground surface with respect to that outside the fence. However, it is difficult to estimate to what extent the surface will be affected
since the measurement campaigns are typically done before the construction of the PV power plant.

> Ground observations may be affected by the change of terrain surface due to the installation of equipment and structures around the sensor installed

The construction of a future PV power plant may also involve changes on the ground surface. In such a case, a study of the historical albedo values makes sense, as long as the ground surface characteristics will revert to the normal condition that existed before. Nature tends to recover its "natural" state. However, this may not always be the case, and possible changes of the soil surface characteristics due to the construction works should be always considered.

Sample of albedometer installations

This example highlights the importance of avoiding obstacles in the instrument's FOV, particularly the PV module.

Fig. 4: Example of a proper installation of an albedometer (prospection phase). Image credit & Copyright: GroundWork Renewables, Inc.

Horizontal vs inclined

Often, there is a second configuration for albedometers that is commonly used in the industry. In this configuration, the separation plane of the instrument is parallel to the plane of the modules (POA).

While this arrangement allows to simultaneously measure the GTI and the irradiance projected on the rear side of the modules (useful for monitoring in the operational phase of the bifacial PV power plants), the POA albedometer configuration does not allow to obtain the albedo of the surface.

> Tilted configurations do not provide surface albedo values according to the definition described

The main difference between the values derived from both configurations lies in the total incident irradiance measured, namely: GHI in the case of the horizontal installation, and GTI in the case of the POA installation [10]. While the horizontal configuration allows to properly derive the ground surface albedo according to the definition, the tilted (POA) configuration does not.

Tilted configuration for albedometers

Fig. 5: Example of a tilted installation of an albedometer (operation phase). Image credit & Copyright: GroundWork Renewables, Inc.

Checking the representativeness of albedo

Covered area

With a pragmatic perspective motivated by practical limitations, a set of albedo values for a single location is intended to be the parameter characterizing reflectiveness of the ground surface of a larger area. Therefore, assessing the representativeness of such value is important.

The inter-comparison of the ground and satellite-based assessments should be restricted to cases, in which the spatial representativeness of the areas covered is equivalent. Due to the spatial variability of the albedo, and the limited size of the FOV of the ground-based instrument (with respect to the footprint of the satellite pixel), this can occur only for large homogeneous surfaces.

> Intercomparison is restricted to the cases in which the spatial representativeness of the areas covered by satellite data and an albedometer are equivalent.

For the case of bifacial PV power plants it is important, especially for big projects, to accurately characterize the surface covered by the PV module field. Thus providing geographical coordinates of a single point inside the area is not sufficient. Rather, boundaries of the entire geographical extent of the PV module area are needed, to allow for analysis of homogeneity of the surface.

Area comparison on a map

Albedo values can represent different areas:

- Satellite pixels of MODIS native projection (parallelograms- shaped, blue-colored, grid resolution approx. 0.5 km)
- Geographical projection with respect to the surface (orange, rectangle with 1 km resolution)
- FOV of an albedometer, assuming an installation height of 2 meters (red circle)
- Hypothetical layout of a PV module field (boundary drawn in fuchsia)

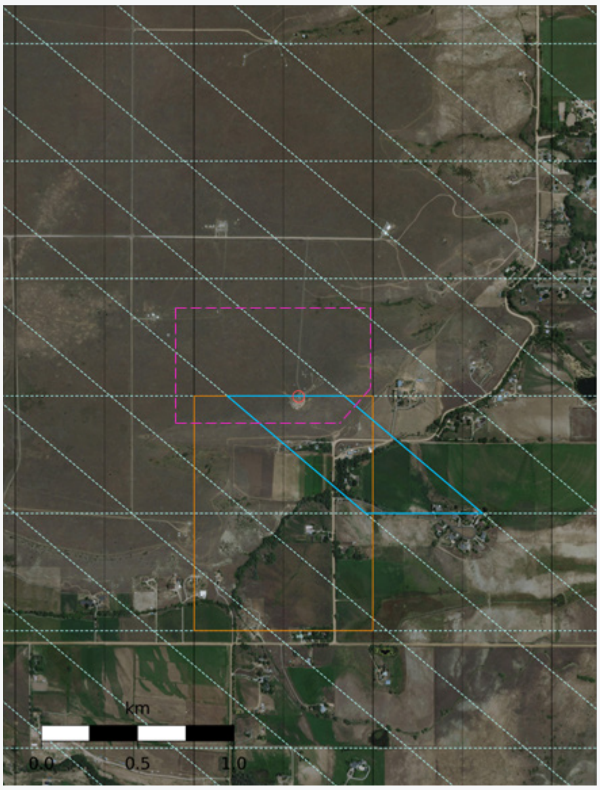

Fig. 6: Satellite map surrounding the SURFRAD radiometric station of Table Mountain (USA).

Surface homogeneity

Albedo characterizes the reflective properties of a particular surface. Therefore, an inherent property of this parameter is its spatial representativeness, which in turn depends on the homogeneity of the surface characteristics [2, 8, 9].

> Representativeness of albedo depends on the homogeneity of the surface characteristics

Because of practical constraints, the surface albedo is usually characterized by a single value that is assumed to be the most representative of the area of interest, i.e. the solar field. The validity of this assumption depends on the spatial variability of albedo in the area.

The spatial representativeness in a specific location directly influences the uncertainty associated with the characterization of albedo. Furthermore, it establishes the possible framework in which the methods of assessing albedo can be used, compared and corrected.

Surface overview

Satellite image of a 35 km x 35 km area surrounding the location where the ground station is located.

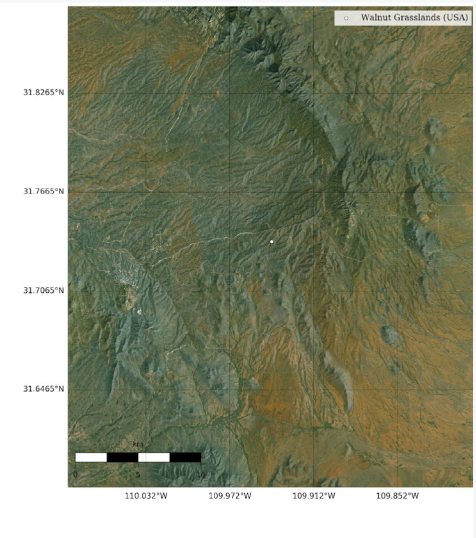

Fig. 7: Surroundings of AmeriFlux radiometric station Walnut Gulch Kendall Grasslands in the USA.

Matching albedometer FOV with satellite pixel

Although ground observations are expected to be the most accurate method, for the size covered by the solar field this does not always have to be the case and it all depends on the particular conditions of the site.

Therefore, the instrument location should be as representative of the solar field as possible.

> Analysis of the location in relation to the layout of the solar field must be made to optimize the representativeness

Satellite pixels (1 km and 0.5 km) containing the geographical position of the albedometer are partially covering surfaces with different characteristics than the surface surrounding the instrument. Moreover, the areas covered by the satellite pixels and the instrument's FOV can be markedly different.

In case that the instrument and the satellite pixel represent different surfaces, it is sometimes a practice to select other nearby satellite pixels with representativeness similar to the site with the albedometer.

Surface analysis

Albedo databases can provide an overview of spatial variability at the resolution provided by the source. The satellite image (left) corresponds to a particular moment in the year, while the albedo data layer (right) represents the annual average. The two are shown together for reference.

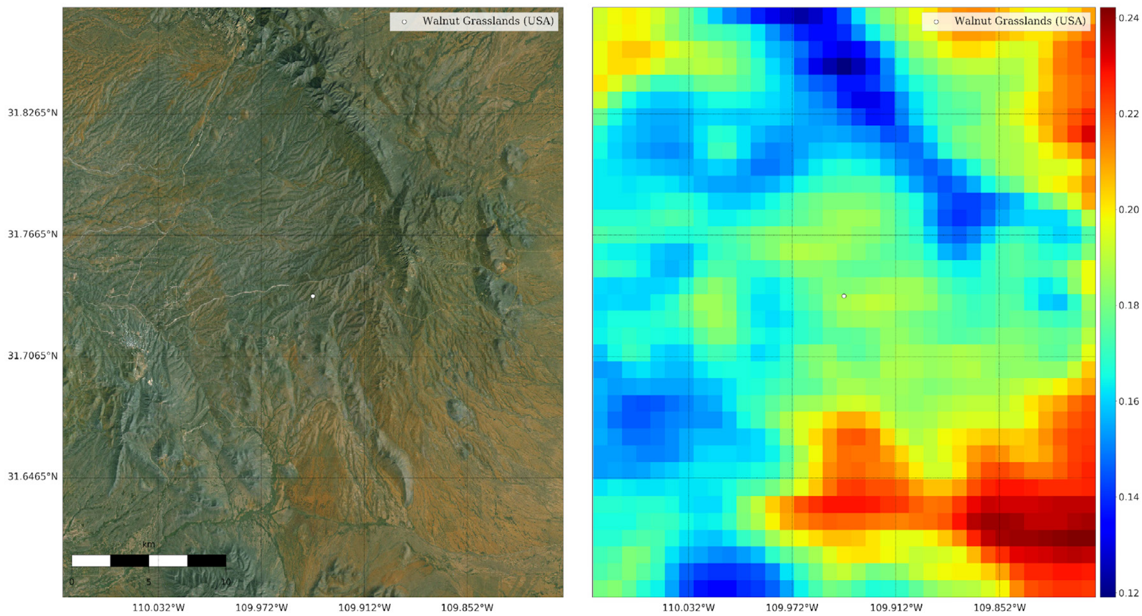

Fig. 8: Satellite image (left) and annual average albedo from Solargis climatological database (1 km resolution) (right) around Walnut Gulch Kendall Grasslands station in the USA.

Reducing bias of albedo values

What to expect from satellite and ground observations

It has not been a practical possibility until today -nor will be in the future- to provide ground-based measurement coverage of any potential solar plant location worldwide for the required length of time. In addition, the FOV of the instrument may be too localized with respect to the size of a solar plant, and hence poorly representative. On the other hand, the finite spatial and temporal resolution of the satellite limits its ability to observe the intra-pixel and intra-day variability of albedo, which can be significant. This makes ground measurements indispensable.

> Satellites and albedometers can be comple-mentary sources of information used for data validation and correction

From the perspective of real applications both observation methods, ground and satellite-based, present their advantages and limitations. They offer complementary sources of information. Except for very few scientific radiometric stations, only the satellite data can provide historical time series at the global coverage. On the other hand, it is only ground measurements that can provide accurate local information at high temporal resolution (1-minute data).

Ground and satellite

	Ground measurement	Satellite observations
Accuracy	Higher accuracy	Lower accuracy
Spatial resolution	Higher spatial resolution	Lower spatial resolution
Temporal resolution	Higher temporal resolution	Lower temporal resolution
Spatial representativeness at utility-scale PV	Represents limited area; more instruments may be needed for heterogeneous surfaces	Represents (averages) surface properties of a larger area
Temporal coverage	Limited temporal coverage	Extensive temporal coverage
Spatial coverage	Needs to be installed at a project site	Global spatial coverage; limited data under cloudy and snowy conditions
Sensitivity to local climate-surface interaction	Represents local climate	Represents regional climate; for site-specific studies may require complementary ground measurements
Costs	Higher costs	Lower costs

Tab. 2: Methods for measuring surface albedo — summary of main features.

Adjusting bias through site-adaptation

For extensive homogeneous surfaces, the satellite estimations are expected to be close (ideally equal) to ground observations. But, often, there is a mismatch because of factors that fundamentally differentiate them. The objective is to characterize those systematic differences and reduce them.

> Site-adaptation methods try to correct the long-term systematic component of the deviations that differentiate satellite and ground-based sources of data

The site-adaptation methods correct the long-term systematic component of the deviations between both sources of data. As a result, the mean bias deviation (MBD) of the satellite with respect to the ground measurements can be reduced to the minimum, while the correction decreases the values of the other deviation metrics, namely mean absolute deviation (MAD) and root mean square deviation (RMSD).

Site-adaptation of albedo daily and monthly values

Site-adaptation is applied to correct the long-term original satellite time-series (period 2011-2015) with one year of ground measurements (2015). Values of the MBD, MAD and RMSD before (denoted as SG-original) and after (denoted as SG-corrected).

Time-series of daily mean (top) and monthly mean (bottom):
- Albedo from ground observations (red line)
- Original satellite albedo from Solargis (blue line)
- Corrected satellite time-series (green line)

Fig. 9: Time-series of daily mean (top) and monthly mean (bottom) for albedo satellite data site-adaptation performed for data at Desert Rock BSRN station (USA).

Technical requirements for ground observations

Poor quality data means uncontrolled uncertainty and the difficulty to find the right reference, needed for site-adaptation. On the other hand, additional analysis of the data characteristics is needed to understand the particularities of the information contained in the time series.

Data quality assessment is the first step needed for the series of measurement values. The quality is assessed for all GHI (Global Horizontal Irradiance), RHI (Reflected Horizontal Irradiance) and ALB (Ground Albedo) data records, and it involves both automatic and visual tests.

> Quality control is applied for all GHI, RHI and ALB data records, and it involves both automatic and visual tests

Automatic procedures identify missing values, time shifts, and compare measurements against sun position and physical limits. Visual inspection, on the other hand, is applied to identify inconsistencies of a more complex nature, such as shading, reflections, soiling, regular data error patterns, and occasional anomalies. Quality control procedures are more powerful when comparing measurements from several (redundant) solar instruments (if available).

Categories of pyranometers

Sensors accuracy is important. “Class A” category instruments (according to ISO 9060:2018) are recommended to get the required accuracy for performing a measurement campaign for a large-scale PV project.

Fig. 10: Hukseflux SRA11 albedometer.

Data inspections

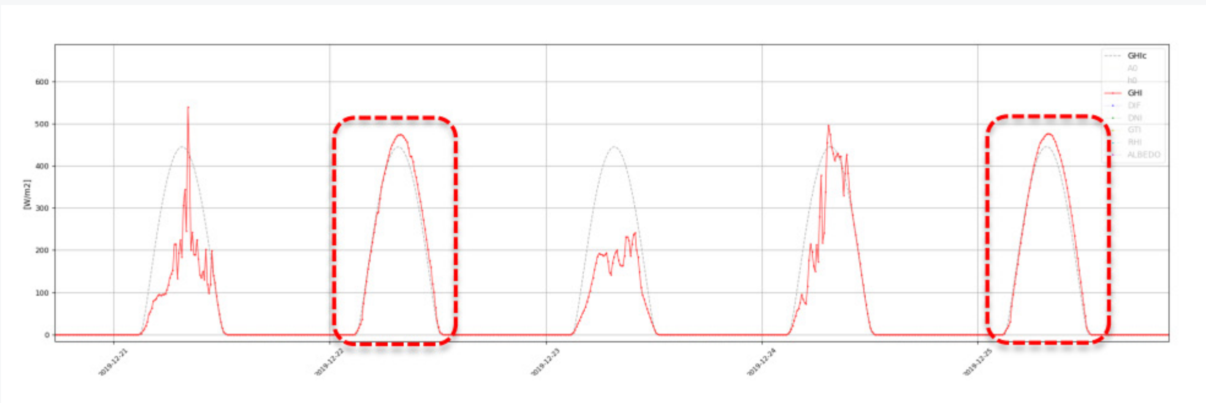

Fig. 11: Example of issues detected in measurements during quality control.

Technical requirements for satellite-based sources

Satellite estimates, for a single platform, can be remarkably consistent over time and are the only practical and reliable alternative that meets the requirements of global coverage with long historical data records.

> It is essential to supply accurate and validated data of a historical period that should be long enough to provide the statistical robustness

Characterization of albedo is a key factor for reliable assessment of the total uncertainty associated with the estimation of energy yield of bifacial PV projects. For that purpose, it is essential to use accurate and validated data of a historical period that is long enough to provide the statistical robustness that allows for a trustworthy foreseeing of the future years during the lifetime of the solar project.

Although satellite-based methods present very valuable characteristics of consistency and robustness, they are not free of inaccuracies due to their inherent limitations. Some of them are related to cloud screening, spectral--to-broadband conversion, atmospheric corrections, assumptions of isotropy and other approximations in the methodology for albedo estimation.

Albedo time series for Almeria, Spain

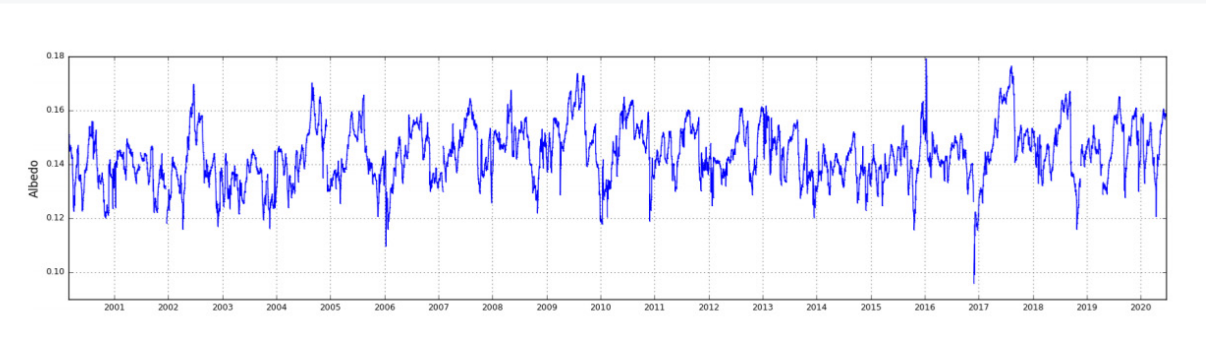

Fig. 12: Albedo time series data for a site in Almeria, Spain.

Assessing snow situations

It is important to identify the elements that define the main signal of the systematic deviation, and separate those that may be part of the noise signal that hinder the correct characterization of the systematic error, like the sporadic outliers due to, for example, detection of occurrence of ephemeral snow.

Sporadic outliers of the satellite detection typically occur when ephemeral snow is present

Snow aging constitutes an element of high uncertainty for the determination of surface albedo, so these events should be treated with special caution or separately.

Snow representation in albedo time series

Ephemeral snow conditions are seen in satellite-based time series differently compared to ground based measurements. In the chart below, this is observed when looking at the peak values recorded in the measurements (— red), and not represented in the satellite-based time series (— blue).

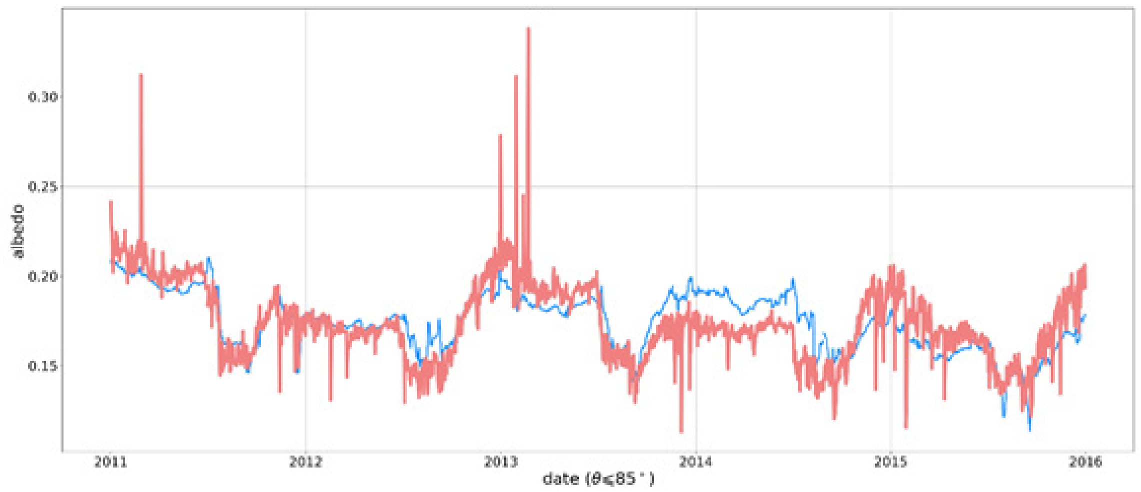

Fig. 13: Time series of albedo for radiometric station site at Walnut Gulch Kendall Grasslands in the USA. Blue: satellite-based time series data; red: ground measurements.

Adequate length of a measurement campaign

Case study: simulation of multiple scenarios

Taking real high-quality measurements for a sample site, the study below reproduces the results of each strategy by simulating multiple campaigns of measurements with a determined number of consecutive days.

Then, the satellite deviations with respect to the values of the different measurement campaigns are corrected for the long-term, and the so-adjusted time series are evaluated against the corresponding ground observations.

At each generated scenario, the campaign's initial date is selected randomly (without repetition) to mimic the real scenario in which it is assumed that any moment may be equally suitable for the measurement campaign. The choice of days of the measurement campaign takes into account that there are no missing values in the satellite data.

> The experiment performed shows the results obtained after simulating multiple campaigns of measurements with different numbers of days

Multiple possible campaigns

All possible combinations of campaigns of more than 160 days long have been tested. For campaigns of less than 160 days, the number of measurement campaigns simulated has been limited to a maximum of 200 per each selection of a certain number of days. Periods were randomly selected along the year 2015 and only valid pairs of observations and satellite data have been considered.

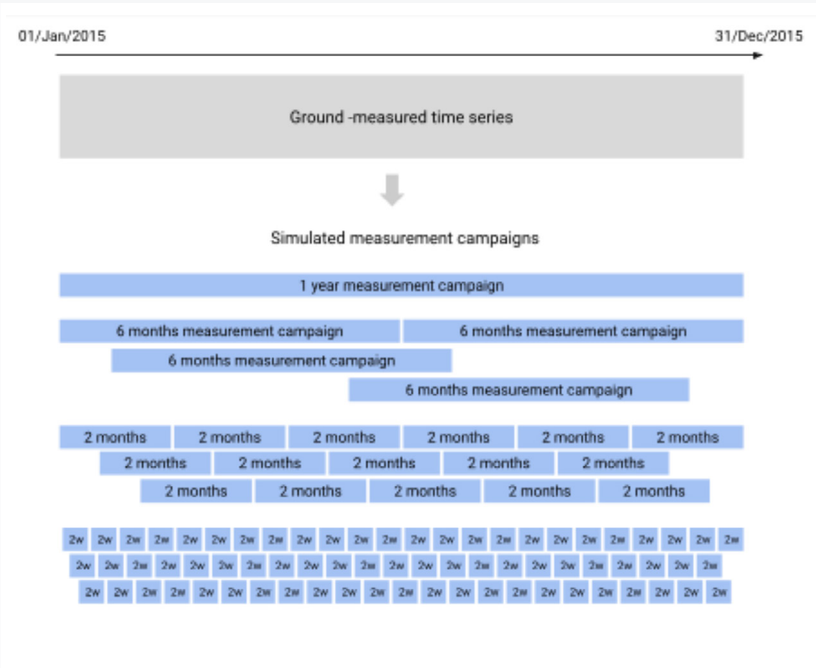

Fig. 14: Samples of multiple measurement campaigns simulated in the study

Campaign approaches

Optical radiometric parameters are among the most complex atmospheric variables to measure with ground-based instrumentation. Consequently, a long-term high-quality measurement campaign of albedo is difficult and costly to maintain. An added difficulty arises when considering the cost and time constraints within solar projects. Due to these challenges, a too simplified perspective is sometimes being taken with respect to albedo measurements for site-adaptation, considering only a few days for the measurement campaigns.

> Due to costs and time constraints, a too simplified perspective is sometimes taken at albedo measurements for site-adaptation, considering just a few days

The underlying methodology of this type of campaign is based on the incorrect assumption that the long-term characterization of albedo can be obtained by extrapolating a-few-days measurements. The measured values are used to adjust the long-term estimates obtained with satellite-based sources in a sort of “light” site-adaptation. In this way, it is intended to reinforce the statistical reliability of the method by means of a so-modified long-term time-series of data. The idea is to give more statistical robustness to campaigns of 3 or 4 days by using longer time series obtained from the satellite.

The only correct method to achieve the lowest uncertainty is by running measurement campaigns for at least one year period.

Risk of under- and overestimations

In the chart, two sets of 3-days campaigns have been highlighted as examples of underestimation (green dots) and overestimation (red dots).

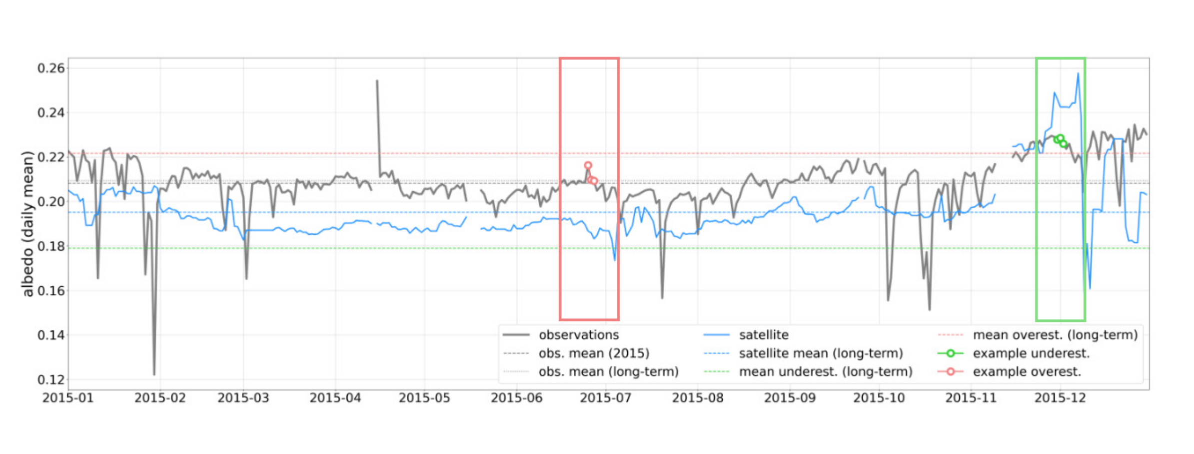

Fig. 15: Sample campaigns of 3-days resulting in under- and overestimations.

Results by length of measured period

Just a few weeks / High risk of increasing the systematic error
From all the simulated campaigns with just a few days/weeks of measurements, the results show many occasions where the subsequently applied correction not only does not improve the satellite systematic bias but introduces an even larger systematic error (in absolute terms).

Two months / Bias starts to be reduced
The mean bias deviations resulting from those comparisons are represented in the figure with blue dots. As it can be observed, the dispersion of results decreases rapidly as the number of days of measurement campaign increases, tending asymptotically to a bias close to zero.

Half-year / Bias reduced significantly
A reasonable improvement that makes it worth the effort to carry out the measurement campaign is considered in this example as one that reduces the systematic error by at least half. Those cases correspond to the blue dots that fall within the area highlighted in grey when the measurement campaigns are 145 days onwards.

One year / Minimum achieved for full adjustment
Differences in data may be affected by monthly and/or seasonal variability. Therefore, a robust site-adaptation requires at least one full year of high-quality measurements.

The high temporal variability of albedo at different scales (daily, monthly, seasonal) causes the adjustments using this correction method to contain a strong random component, and thus getting the right fit with only a few days of measurements is largely a matter of chance, as we show in this study.

> Site-adaptation requires at least one full year of high-quality albedo measurements

Results of applying adjustments for campaigns with different lengths

Each blue dot represents bias deviations of the satellite long-term estimations corrected with the data collected with simulated measurement campaigns with different numbers of days of duration (x-axis).

- Positive values of the mean bias deviations indicate an overestimation of the satellite with respect to the ground observation; negative values indicate underestimation.
- Boxplots are shown for statistical reference, along with the mean and median of the distribution of the mean bias deviations.

- The grey zone indicates the range of values lower than or equal to the half of the satellite actual mean bias deviation
(— orange horizontal line), which is considered to be the acceptance range of error after applying corrections:

  - Systematic error: MBD= -0.014
  - Acceptance range of error after correction: |MBD|/2 = ±0.007

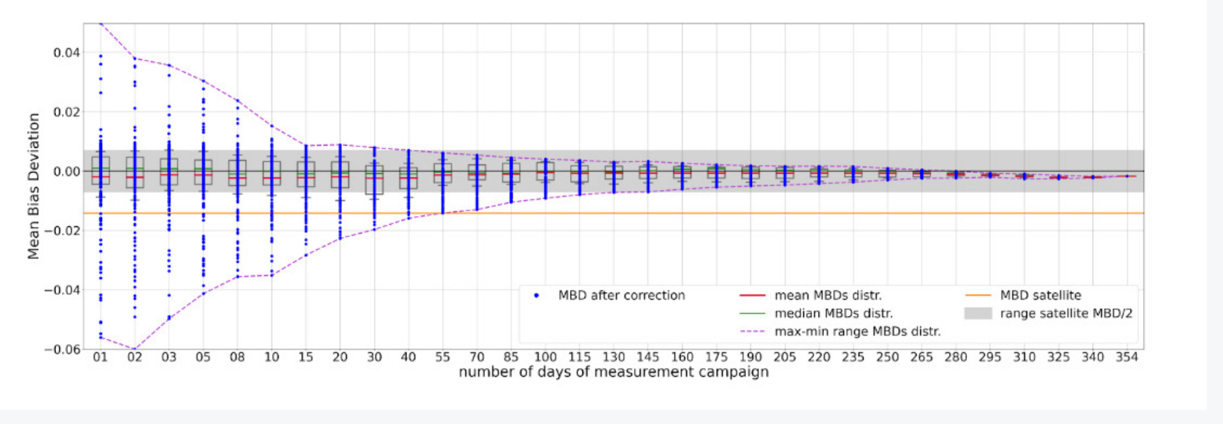

Fig. 16: Results of an experiment conducted for albedo data measured in a sample site.

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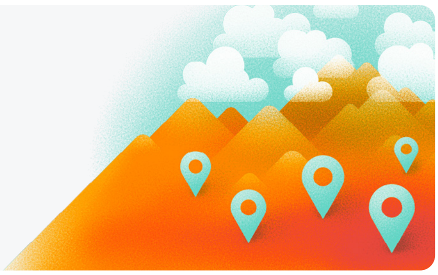
Conclusion

- Site-adaptation can be applied after a data preprocessing and qualification, to ensure that the basic requirements for ground data are met, namely: representativeness of the measured albedo, data quality, and adequate length of measurements.
- During the site selection and installation, the height of instruments, obstacles and spatial representativeness are to be considered.
- As a consequence of the temporal variability of albedo, there is a wide dispersion of plausible results from measuring campaigns depending on the length period measured. Fewer days of measuring generates in many cases larger errors than those present in the satellite data.
- Albedo cannot be characterized by a small sample of ground measured data collected in a few days, nor can this data be considered usable for correcting the satellite estimations.

Instrumentation	Quality (class A, according to ISO 9060:2018)
	Installation (height, obstacles)
	O&M
Ground-measured data	Quality control
	Analysis of the information contained in the time-series
Satellite-based estimation	Analysis of the correlation between the ground measurements and the satellite estimations at different time scales
Period of measurements	1 complete year of data measurements
Representativeness	Study of the surface characteristics for the areas covered by the instrument's FOV, satellite pixel, and PV power plant layout
Snow	The snow conditions should be considered separately

Tab. 3: Elements to be considered when using ground measurements for site adaptation of satellite albedo time series.



Text and research by Vicente Lara, Senior Researcher at Solargis

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This publication has been prepared with the help of other members of the Solargis team. Special thanks to those who made the effort to make available the data used in this work.

Further reading

[1] Albedo white paper Part I
[2] Albedo methodology section in Solargis web site
[3] Albedo data accessible from Prospect app

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